Boundary condition sensitivity in solar convection experiments

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Numerical Models can be considered either simulations (attempts to reproduce reality) or experiments (attempts to learn something about a controlled process, *not necessarily physically realizable*).

It is generally held that:

> " Nobody believes a the results of a numerical model except the modeler, while everyone believes an experiment except the experimentalist"
>
> (a reworking of an A. Einstein quote)

V,V and UQ argues against this.

The fundamental cause of trouble in the world today is that the stupid are cocksure while the intelligent are full of doubt. – Bertrand Russell (stolen from Carlo's email)

The less data you've collected the easier it is to understand.

Models of the solar convective envelope

The observational constraints – radiative and helioseismic signatures

What is being attempted?
What are the difficulties?

Focus on validation:
Are the observational constraints sufficient?
Which parts of the model are being validated by available observations?

ASH (Anelastic Spherical Harmonic):
- Global anelastic dynamics of an ideal gas in a rotating spherical shell

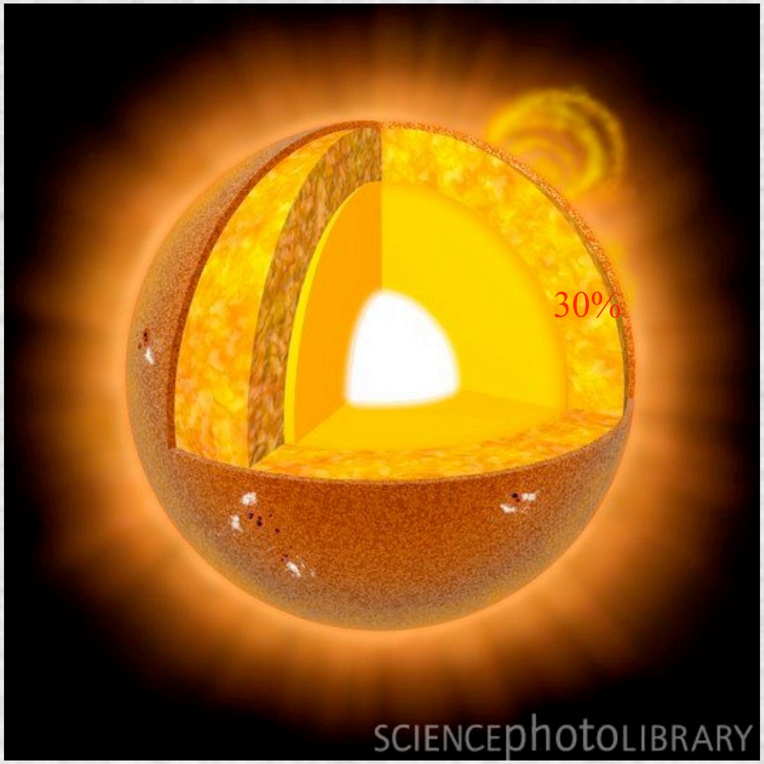
Mark Miesch (HAO/NCAR)

CSS (Compressible Spherical Segment):
- Compressible dynamics of an ideal gas in a rotating shell segment

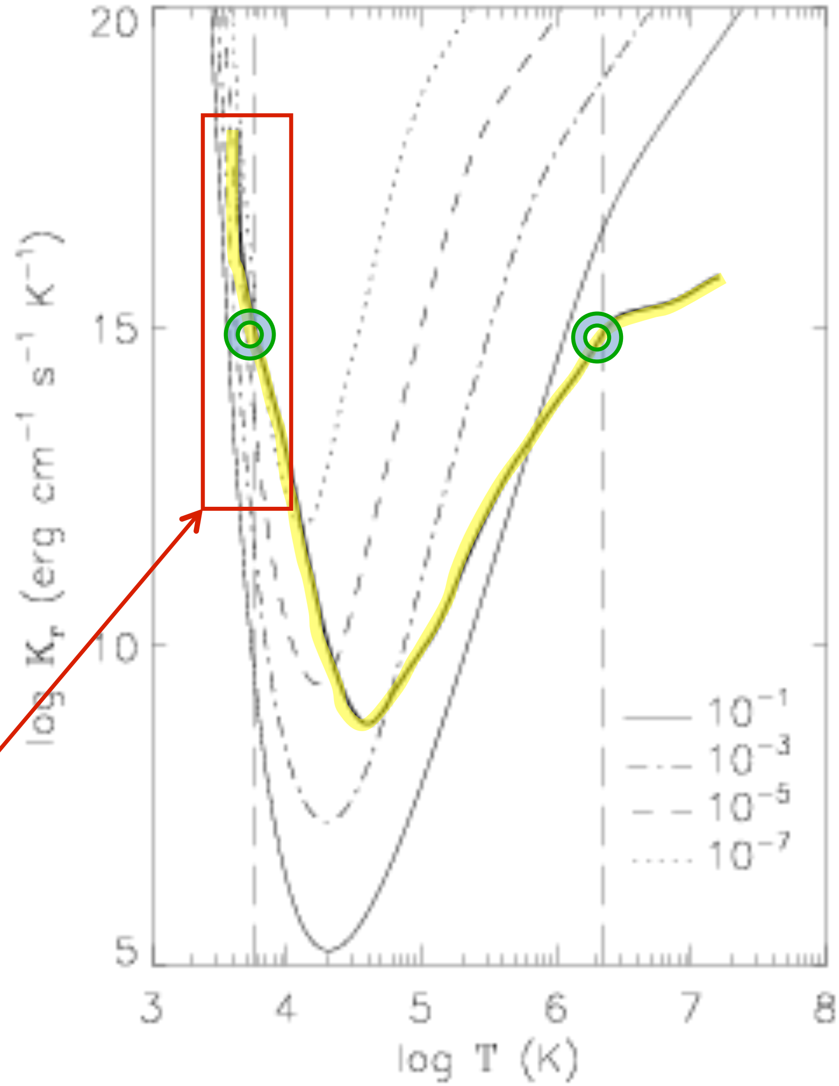
Kyle Augustson (University of Colorado, Boulder)

MSC (Modular Staggered Convection):
- Compressible dynamics of a plane parallel layer of solar plasma with radiative transfer

Åke Nordlund (University of Copenhagen) and Bob Stein (Michigan State)



$$K_r = \frac{16\sigma T^3}{3\bar{\kappa}\rho}$$

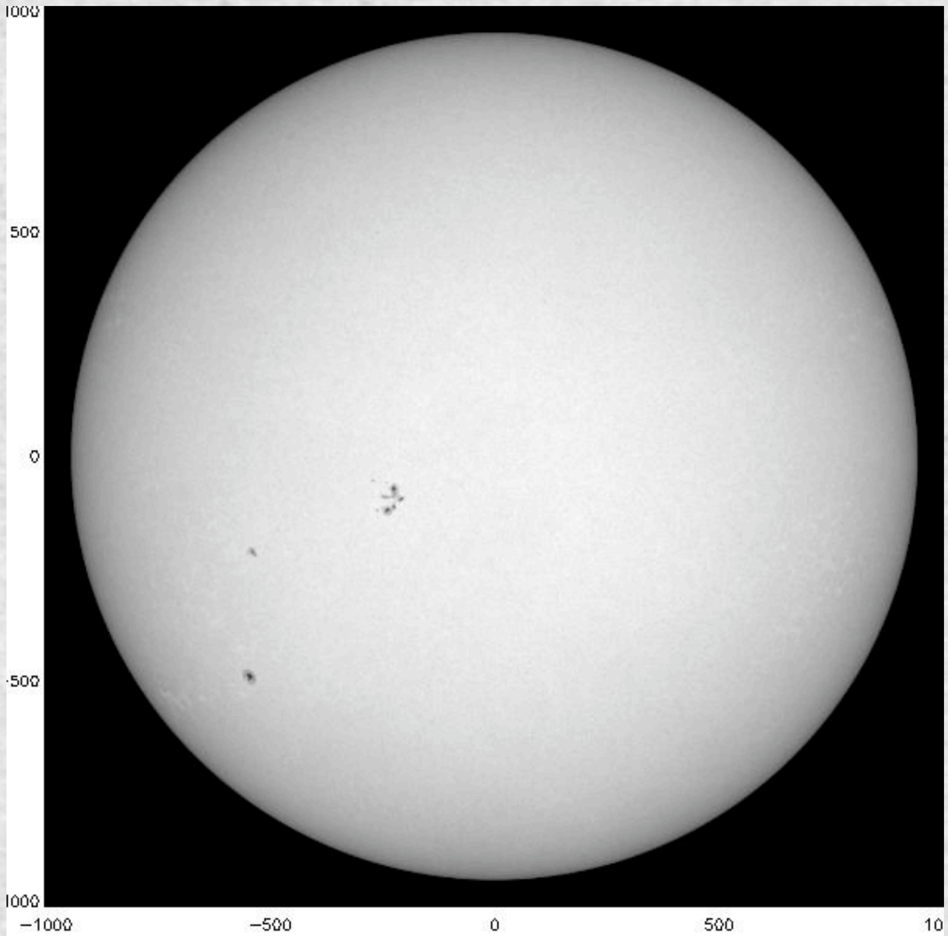


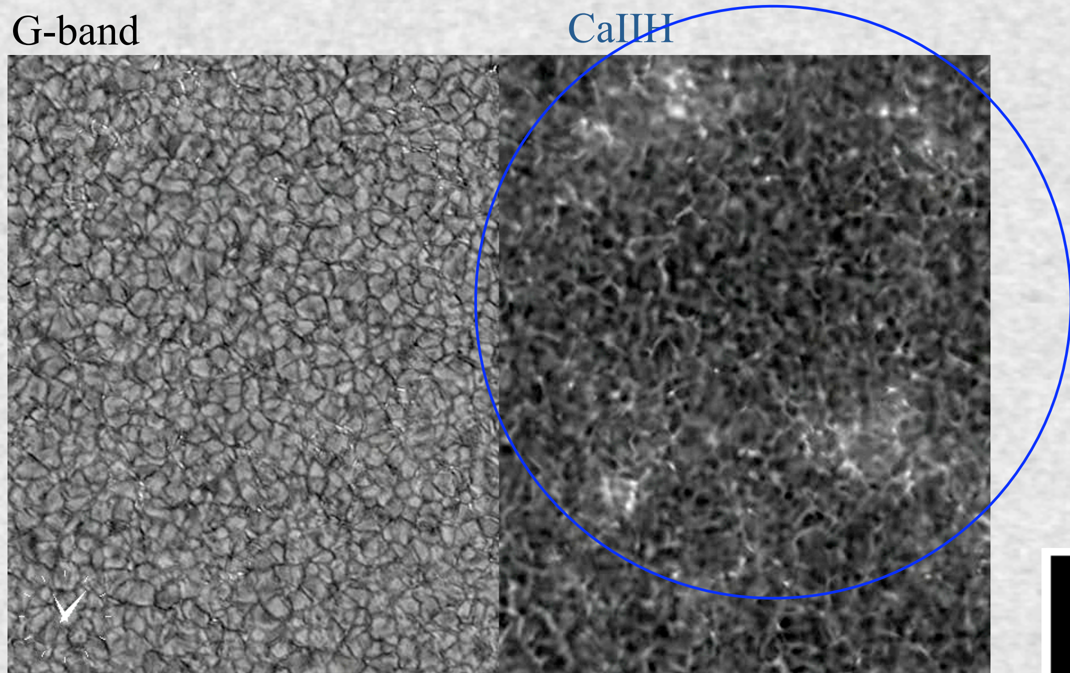
Rapid transition from convective transport to free streaming radiation

Observations:

Direct validation of models is confined to two possibilities:

- Comparisons with observed properties of granulation in the photosphere
- Reproduction of global scale flows detected by helioseismology

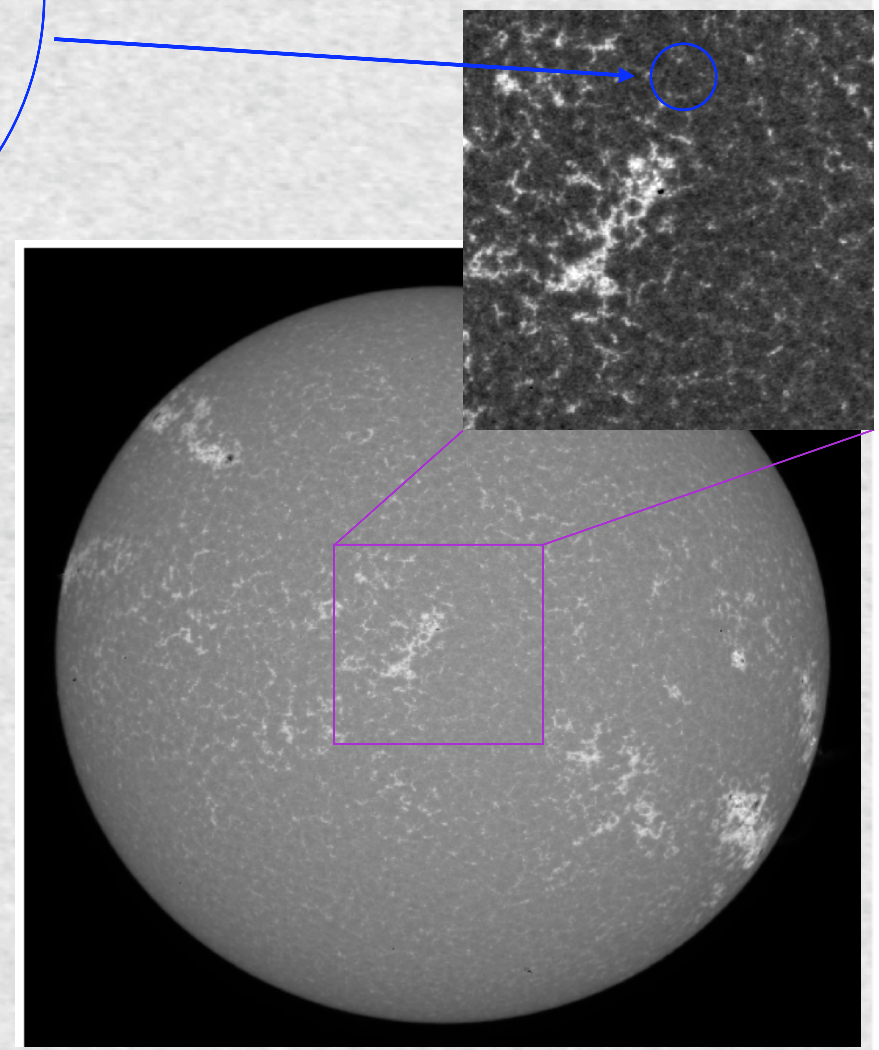




Dutch Open Telescope

Supergranulation
(Hart 1954, Leighton et al. 1962)
- 32000km scale
- 400m/s horizontal flow
- 20hr lifetime

Ro ~ 2


PSPT 20 March 2001 1731UT 393.5nm

Granulation (Herschel 1801)
- 1000km scale
- 1000m/s vertical flow
- 0.2hr lifetime

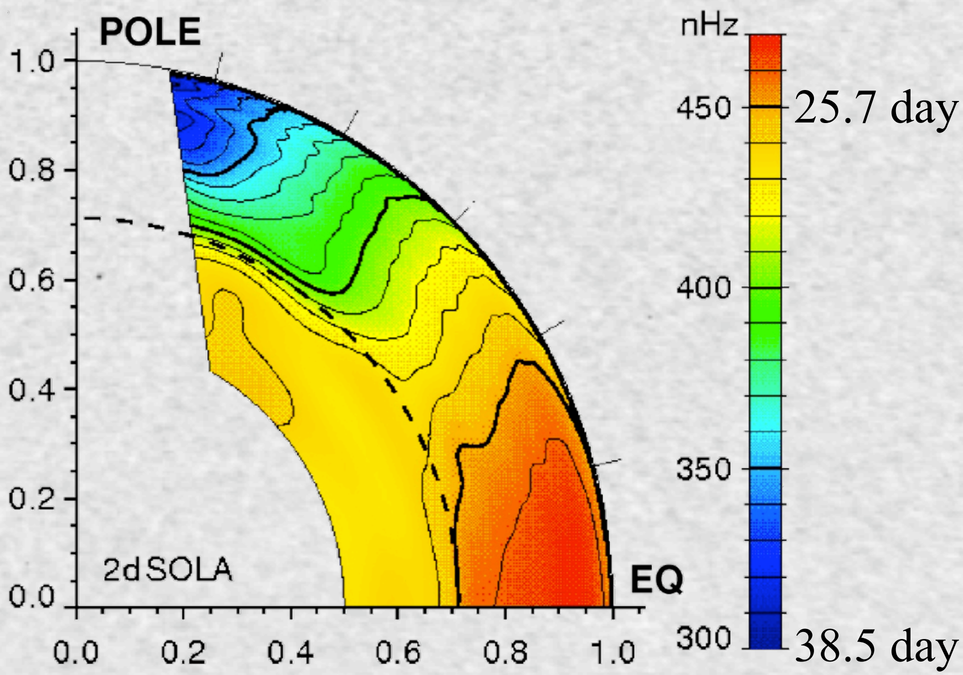
Ro ~ 200

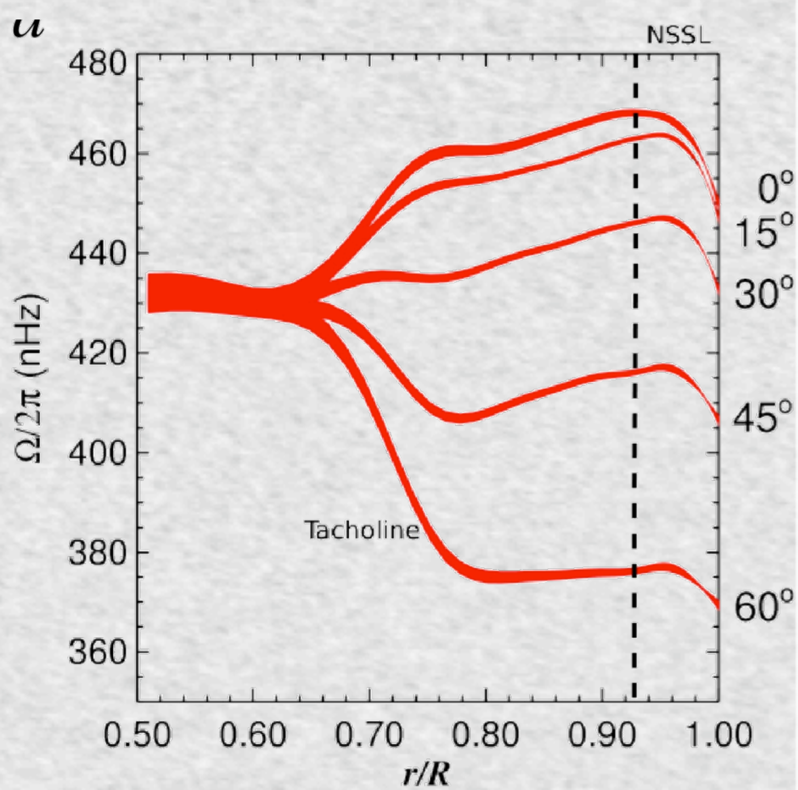
Global scale motions

- Depth of convection zone, ~200Mm
- Transit time, ~23days
- Large scale convection (giant cells)?

Ro ~ 0.01

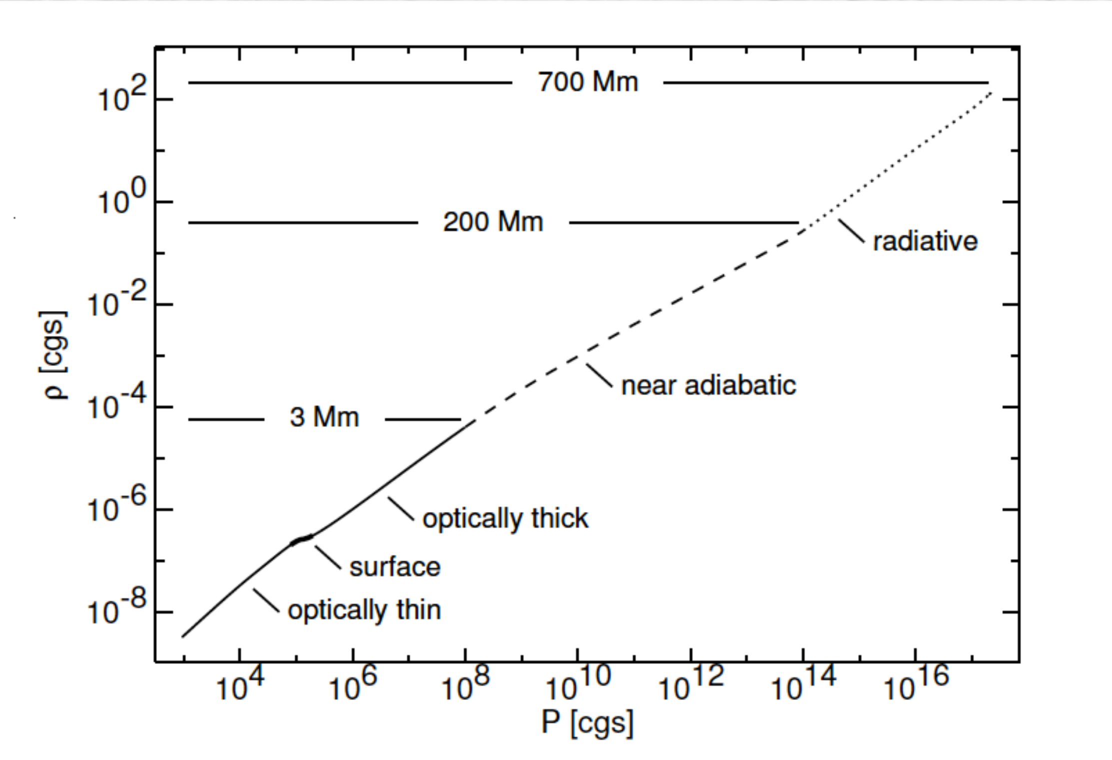
Helioseismic global inversions





Modeling efforts span multiple physical domains:

- highly compressible radiative boundary layer
- region of partial hydrogen and helium ionization
- nearly adiabatic interior with 10^4 density contrast
- overshoot region at based of convection zone



Nordlund, Stein, and Asplund 2009

Solar convection experiments (numerical):

Solve the fully compressible or anelastic Navier-Stokes equations with

- hyperviscosity, slope limited diffusion, or subgrid model
- radiative transfer (LTE, 4 opacity bins) or thermal diffusion with subgrid model
- ideal gas eos or solar model table lookup

$$\frac{\partial \ln \rho}{\partial t} = -\mathbf{u} \cdot \nabla \ln \rho - \nabla \cdot \mathbf{u} \, ,$$

$$\frac{\partial \mathbf{u}}{\partial t} = -\mathbf{u} \cdot \nabla \mathbf{u} + \mathbf{g} - \frac{P}{\rho} \nabla \ln P + \frac{1}{\rho} \nabla \cdot \tau \, ,$$

$$\frac{\partial e}{\partial t} = -\mathbf{u} \cdot \nabla e - \frac{P}{\rho} \nabla \cdot \mathbf{u} + Q_{\mathrm{rad}} + Q_{\mathrm{visc}}$$

$$\nabla \cdot (\overline{\rho} \boldsymbol{v}) = 0,$$

$$\overline{\rho} \frac{\partial \boldsymbol{v}}{\partial t} + \overline{\rho} (\boldsymbol{v} \cdot \nabla) \boldsymbol{v} = -\nabla P - \rho g \hat{\boldsymbol{r}} - 2 \overline{\rho} (\boldsymbol{\Omega}_* \times \boldsymbol{v}) - \nabla \cdot \mathbf{D} - \hat{\boldsymbol{r}} \left(\frac{d \overline{P}}{dr} + \overline{\rho} g \right)$$

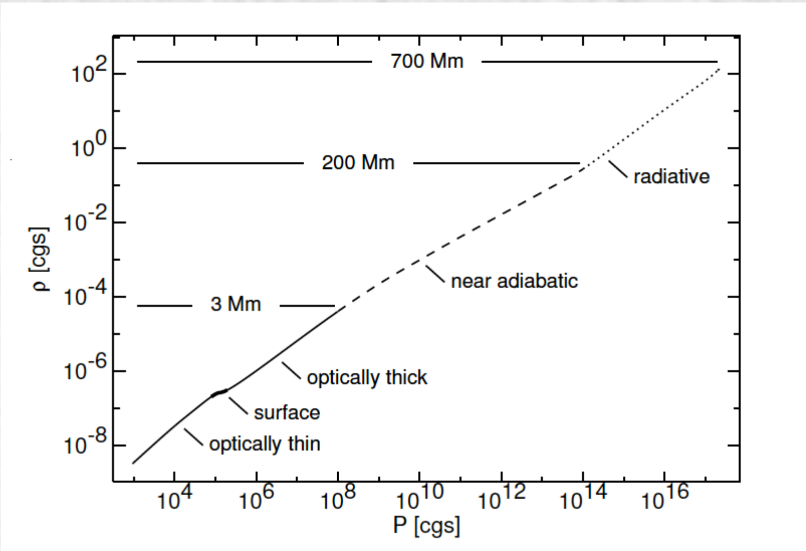
$$\overline{\rho} \overline{T} \left(\frac{\partial S}{\partial t} + \boldsymbol{v} \cdot \nabla S \right) = -\overline{\rho} \overline{T} v_r \frac{d \overline{S}}{dr} + \nabla \cdot \left[\kappa_r \overline{\rho} C_P \nabla (T + \overline{T}) + \kappa \overline{\rho} \overline{T} \nabla S + \kappa_0 \overline{\rho} \overline{T} \frac{d \overline{S}}{dr} \hat{\boldsymbol{r}} \right] + \overline{\phi}.$$

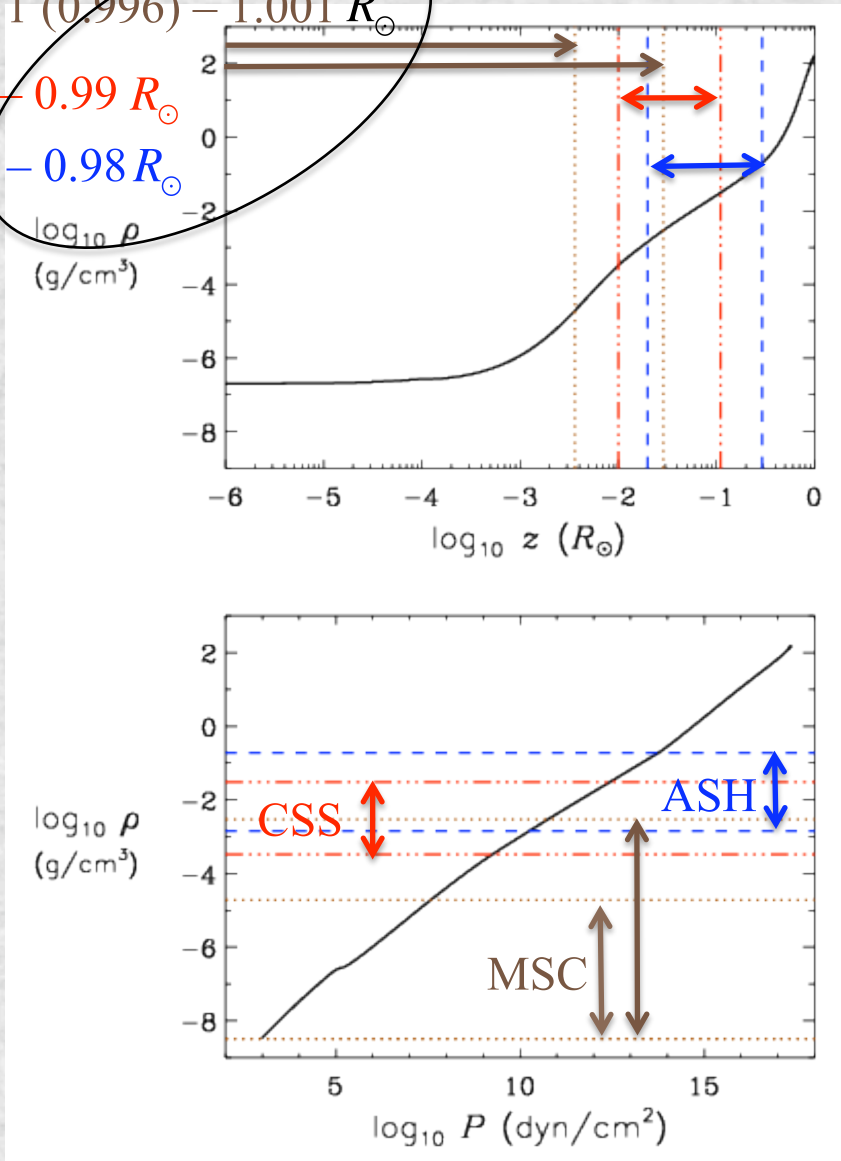
Codes span different domains of applicability – Code boundaries are problematic.

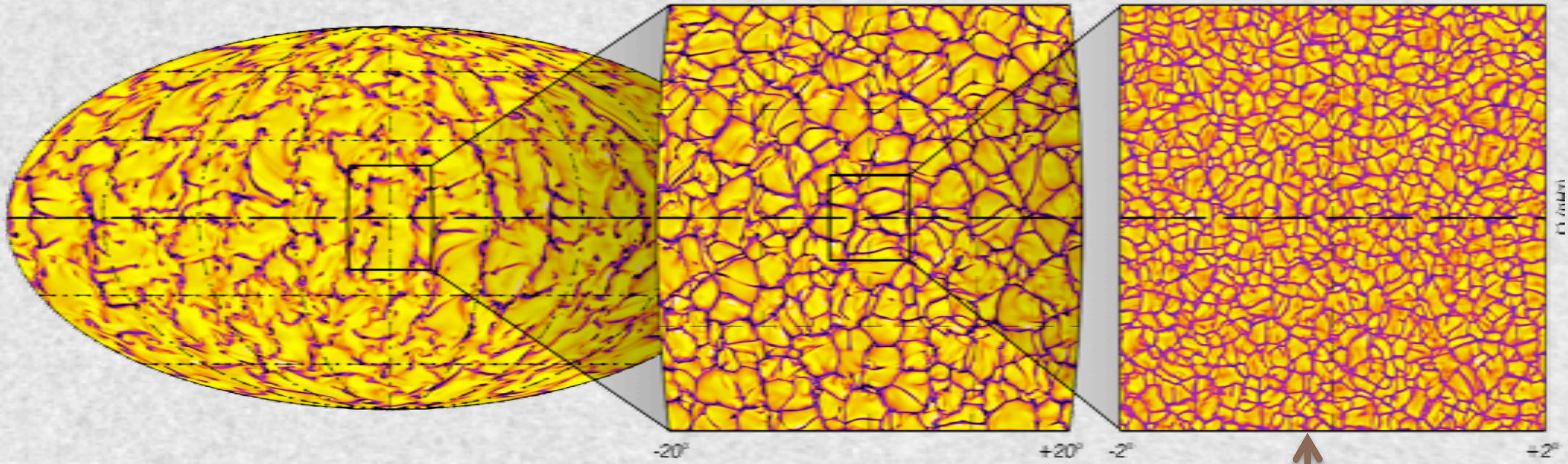
Modular Staggered Convection — MSC: 0.971 (0.996) – 1.001 $R_\odot$

Compressible Spherical Segment — CSS: 0.89 – 0.99 $R_\odot$

Anelastic Spherical Harmonic — ASH: 0.71 – 0.98 $R_\odot$







ASH
(Anelastic Spherical Harmonic):

• Global ane
ideal gas in
shell

• Resolution
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• Stress free
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• Lower bou
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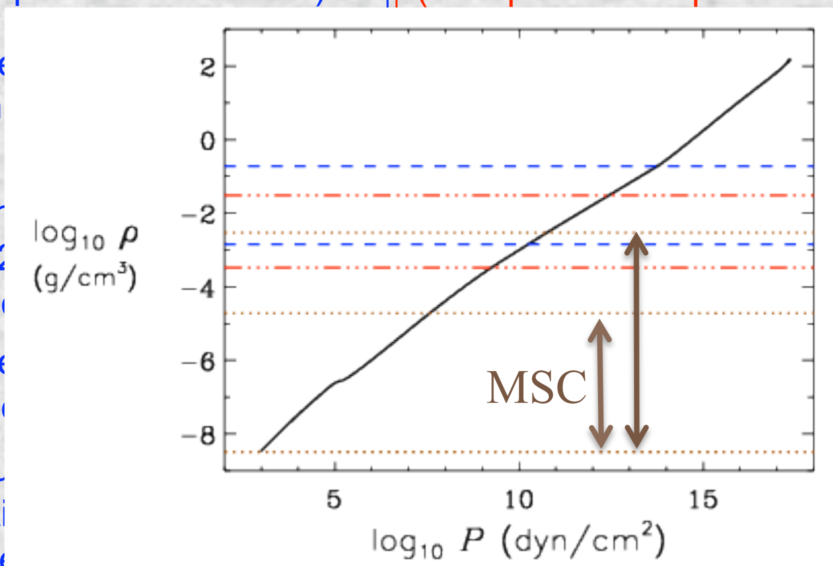
• Upper boundary (region) includes enhanced unresolved radial flux



CSS
(Compressible Spherical Segment):

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jets (mimicking statistics of down-flows in high resolution granulation simulations)

MSC
(Modular Staggered Convection):

• Compressible dynamics of a plane parallel layer of solar plasma with radiative transfer

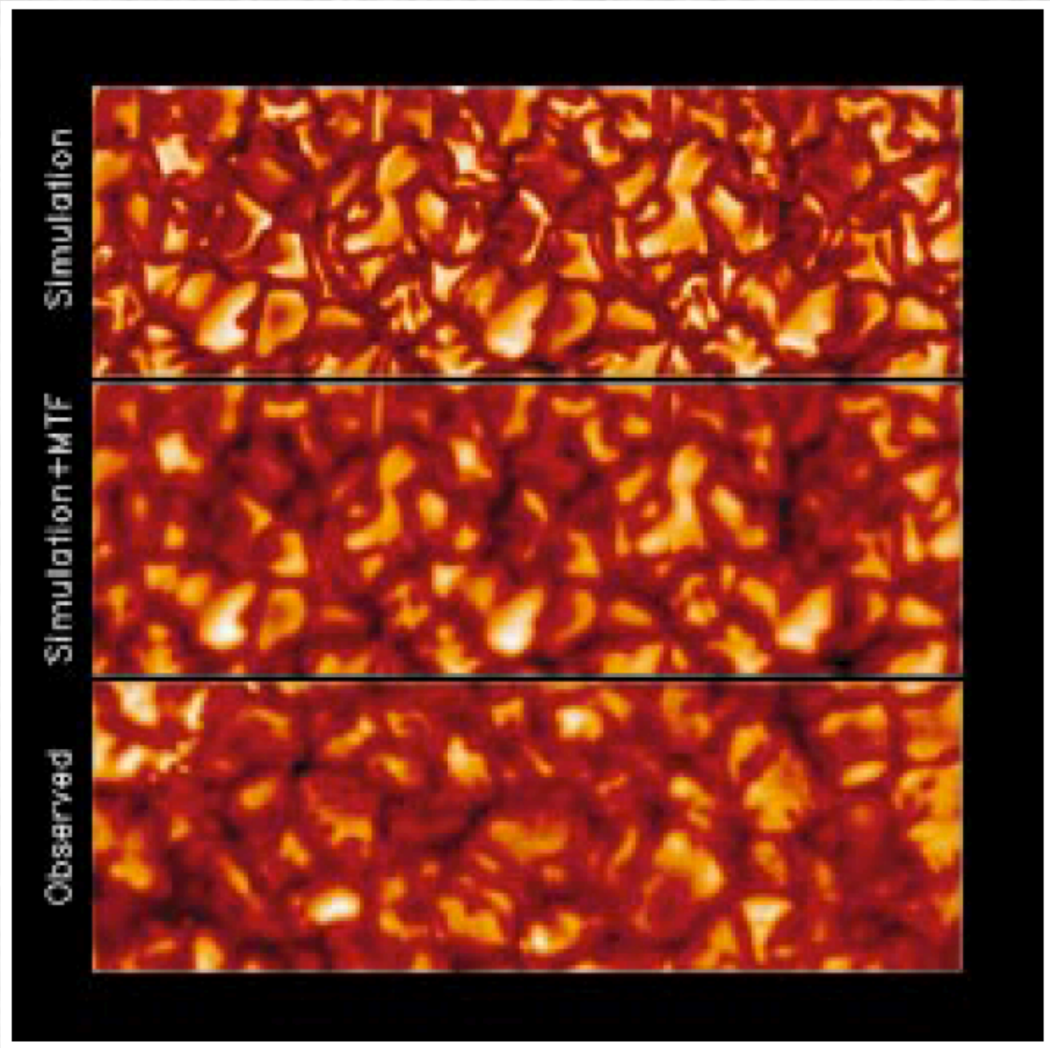
• 6^{th} order compact finite differences, 3^{rd} order Runge-Kutta time-stepping scheme

• Horizontally periodic, open upper and lower boundaries – leave outflows unaffected

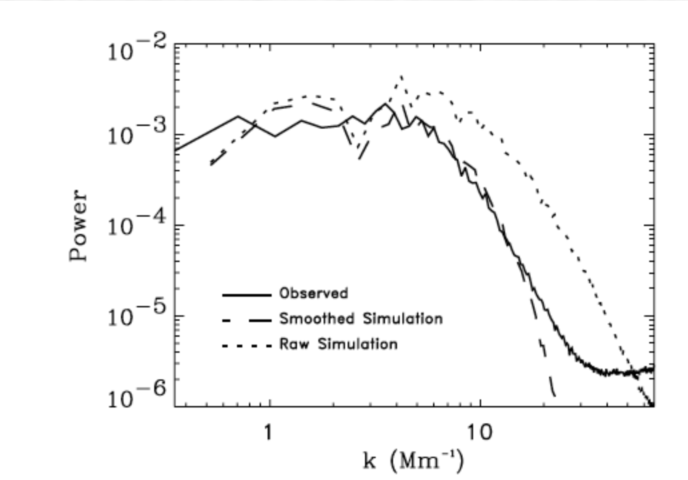
• Lower boundary: entropy of inflows specified to meet solar flux, lower surface constant pressure

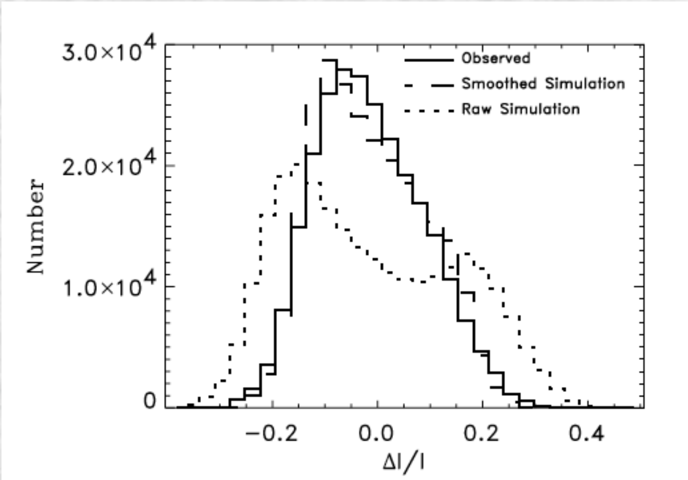
Simulation vs. Observations (MSC):

Stein and Nordlund 2000, Nordlund, Stein, and Asplund 2009

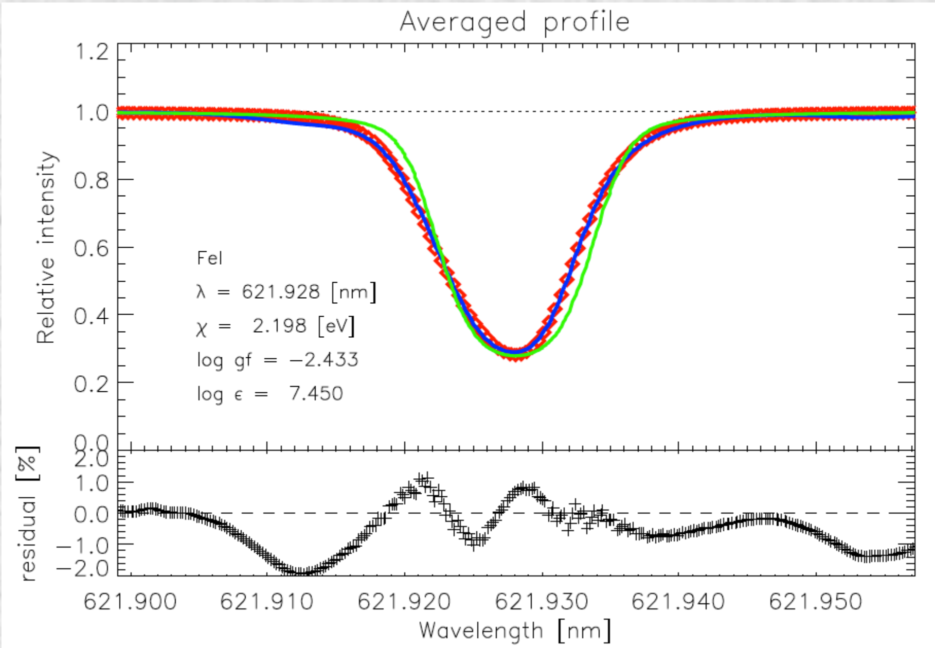


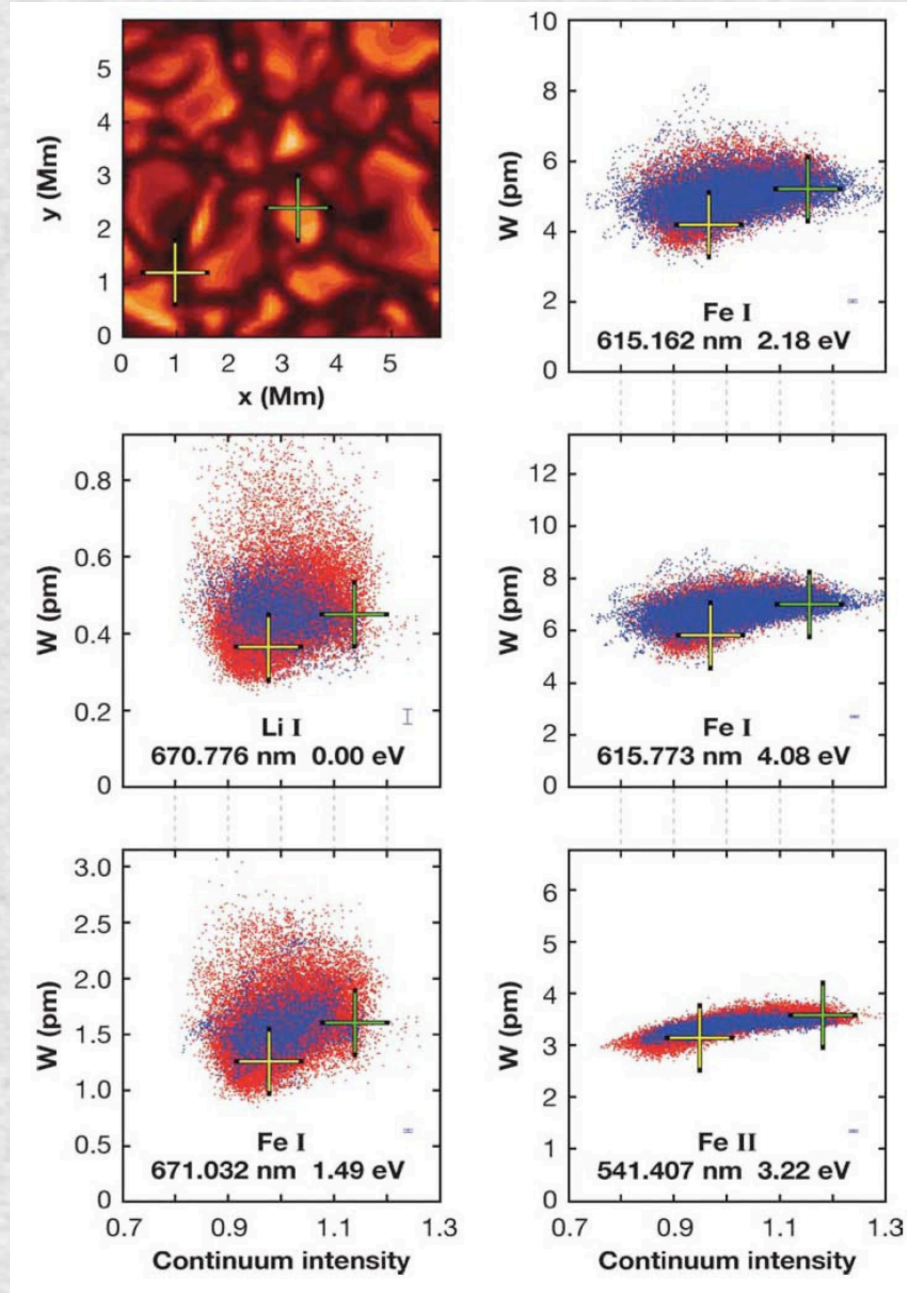
Viewgraph norm





Granular flow statistics and dynamics in good qualitative agreement

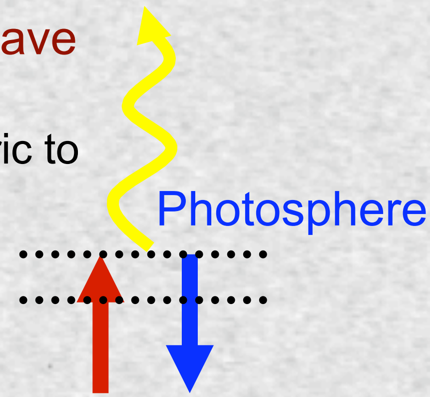




Spectral line properties compared
with solar disk center measurements

What physical processes in the code have been validated?

Observed flow properties may be are generic to a radiatively cooled boundary layer of solar composition

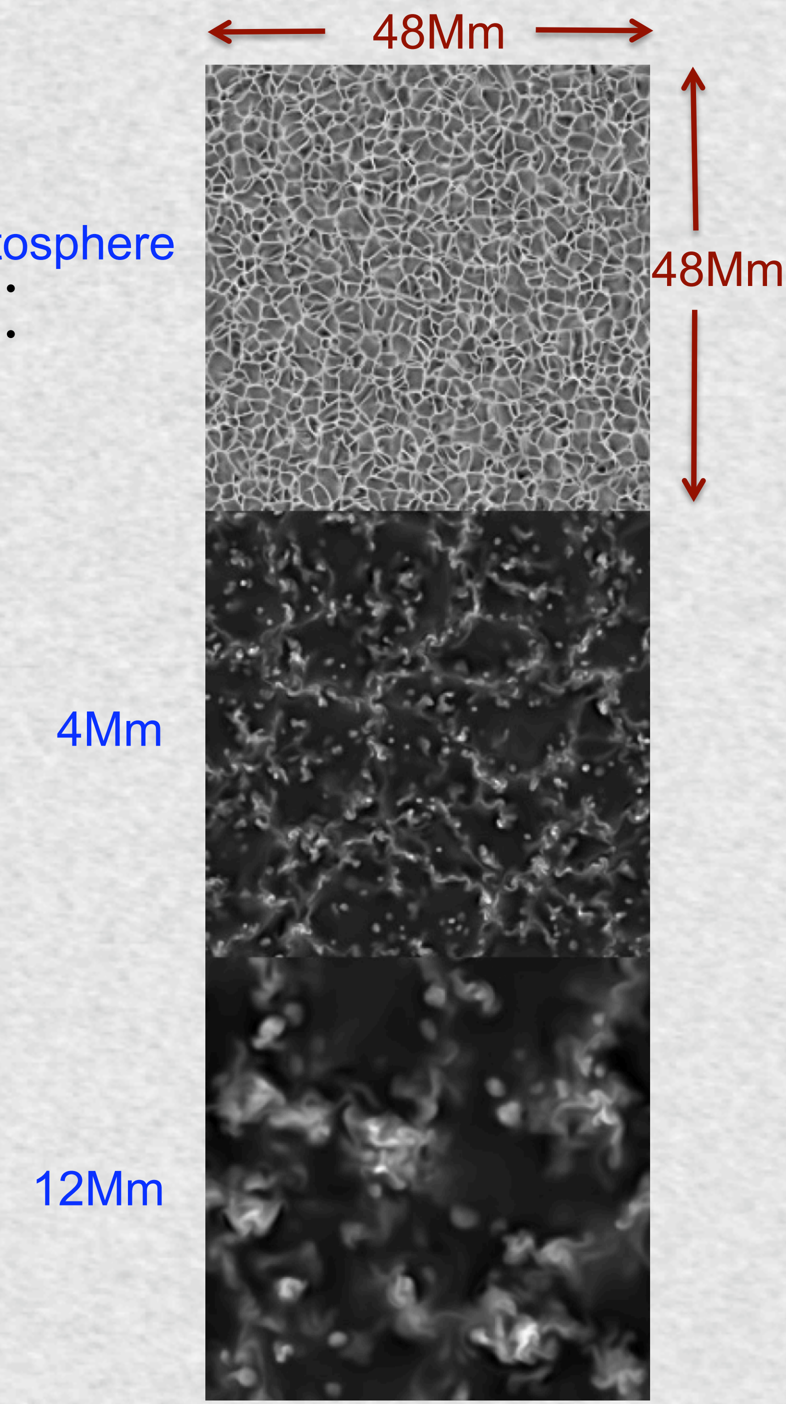


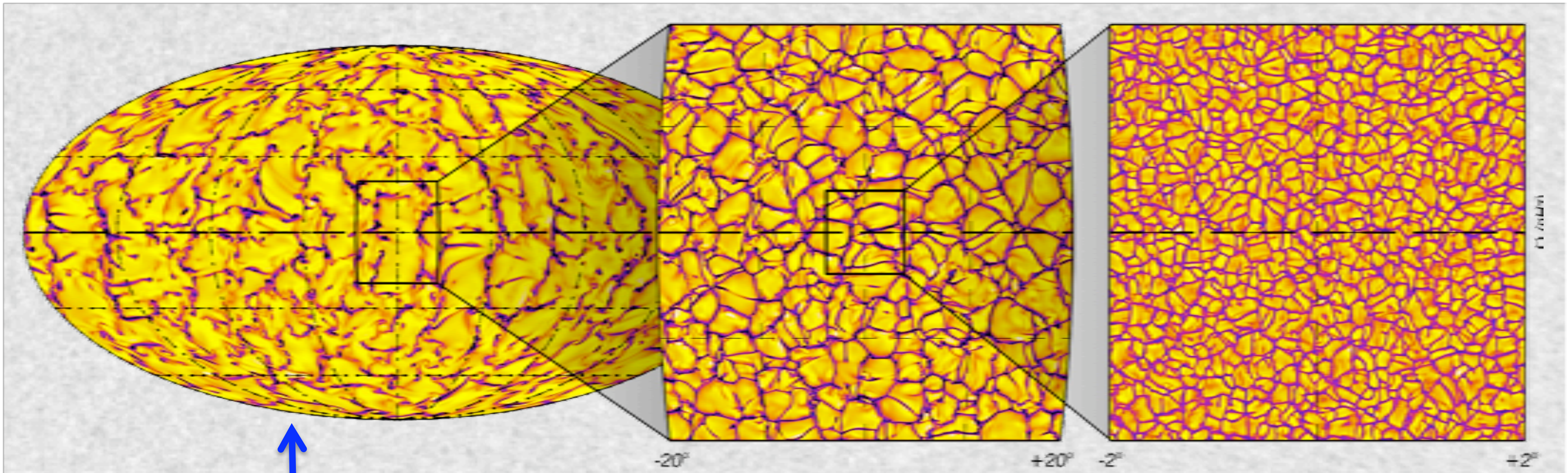
$$\sigma T^4 = \Delta h \rho w \quad \Longrightarrow \quad \boxed{w \approx 1.5\mathrm{km/s}}$$

Granulation dynamics is largely downflow dominated

The combination of a strongly radiatively cooled photosphere and an open lower boundary boundary that leaves downflows untouched and adjusts the upflows in response determines the solution characteristics (top-down dynamics)

The code is tailored to granulation but can not investigate the origin of larger scale motions in the photosphere if those have a bottom-up causes





ASH
(Anelastic Spherical Harmonic):

- Global anelastic dynamics of an ideal gas in a rotating spherical shell
- Resolutions up to 257x1024x2048 (radial, latitudinal, longitudinal)
- Stress free and impenetrable upper and lower boundaries
- Lower boundary condition includes latitudinal entropy gradient (Rempel 2005)
- Upper boundary (region) includes enhanced unresolved radial flux

CSS
(Compressible Spherical Segment):

- Compres
gas in a ro
- 6^{th} order
spatial dis
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- Longitud
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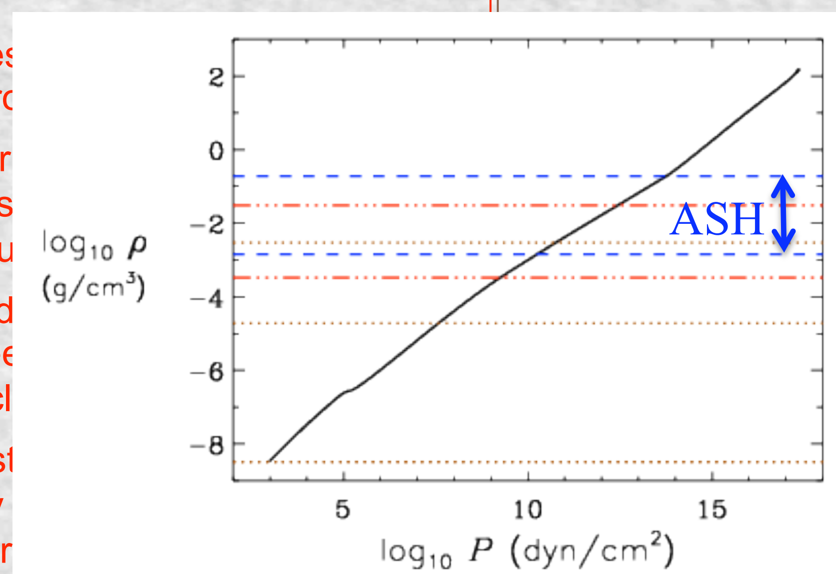

MSC
(Modular Staggered Convection):

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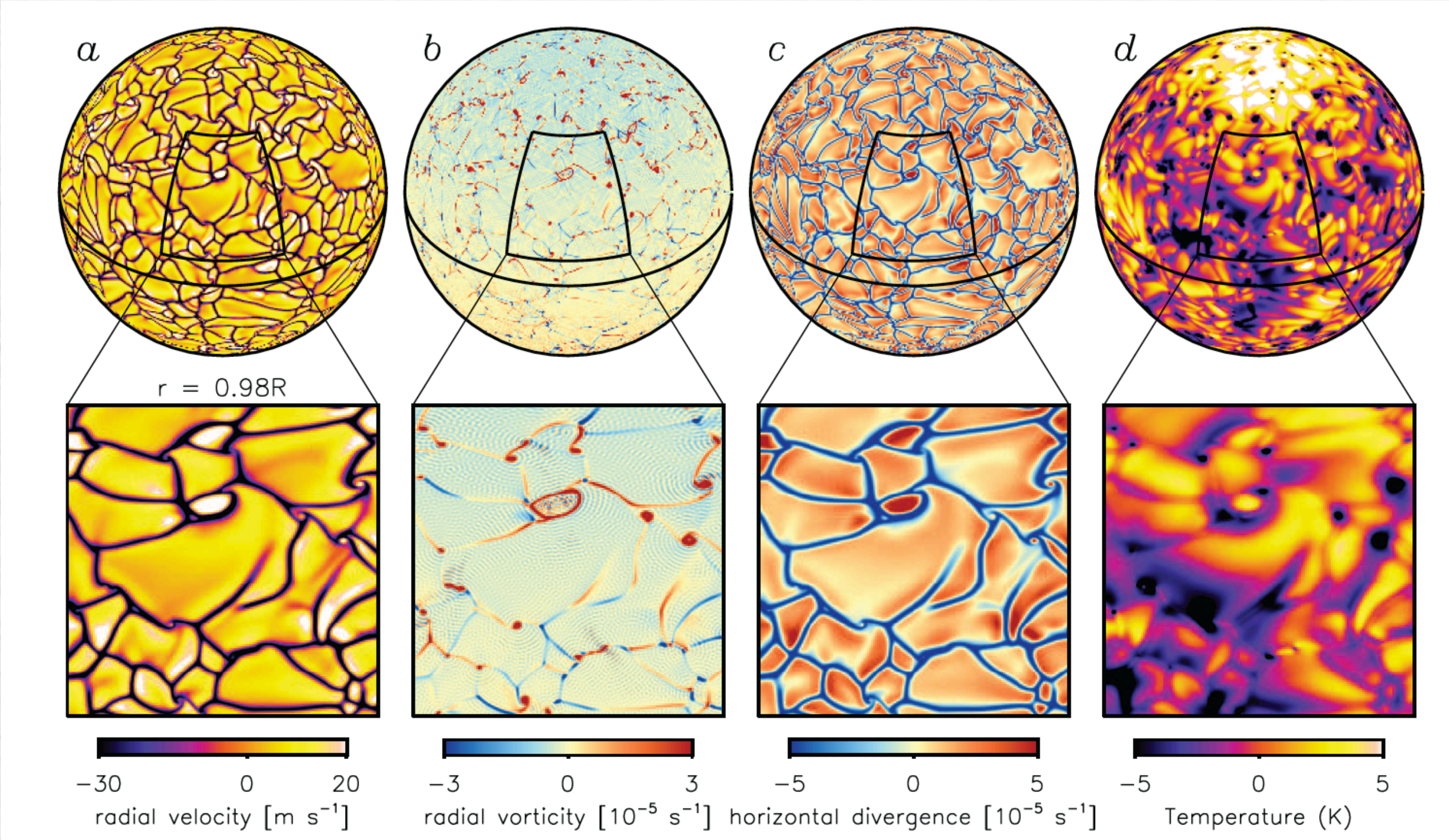
In ASH the opposite problem occurs:

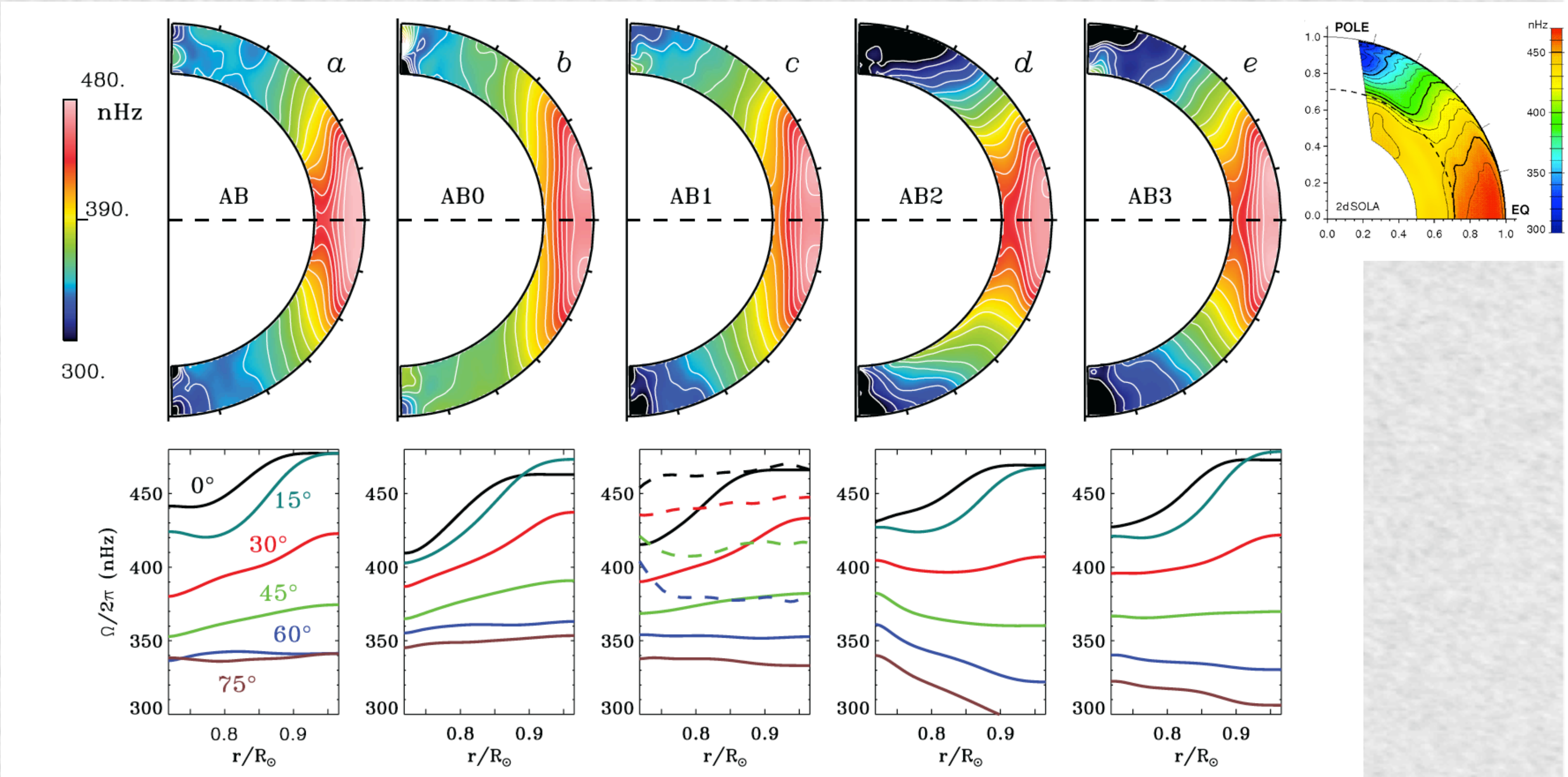
At the top of the domain there is a thermal boundary layer that shouldn't be there



STRUCTURE AND EVOLUTION OF GIANT CELLS IN GLOBAL MODELS OF SOLAR CONVECTION

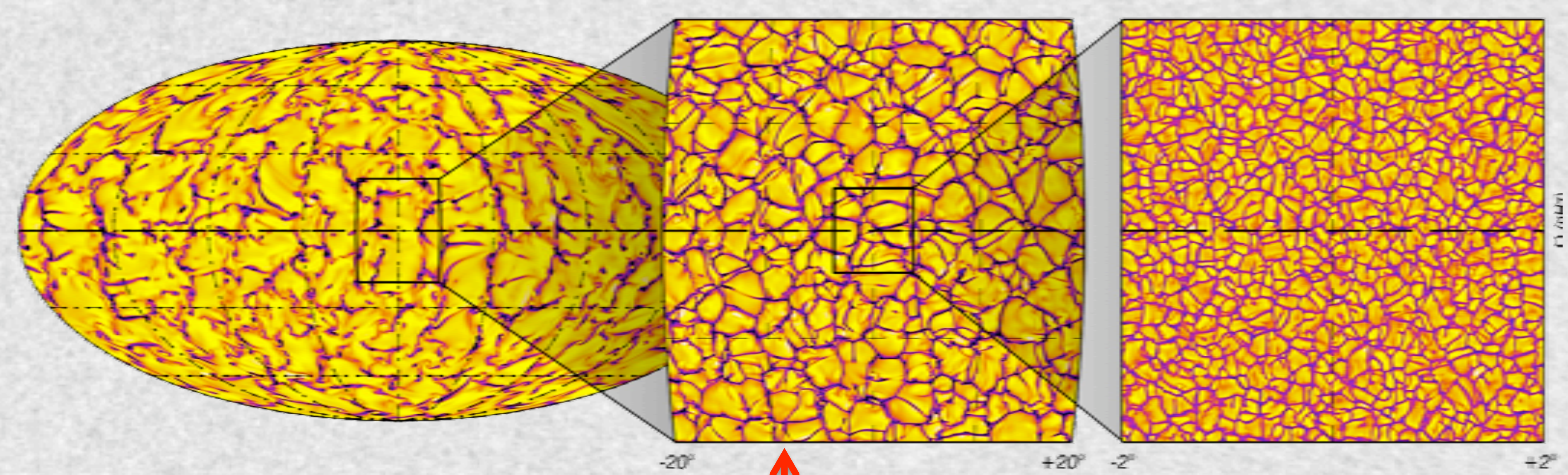
The Astrophysical Journal, 673:557–575, 2008 January 20

Simulation vs. Observations (ASH):



Miesch, Brun, and Toomre 2006

- Imposed latitudinal entropy gradient at lower boundary improves differential rotation profile (Rempel 2005)
- Surface shear layer unattainable



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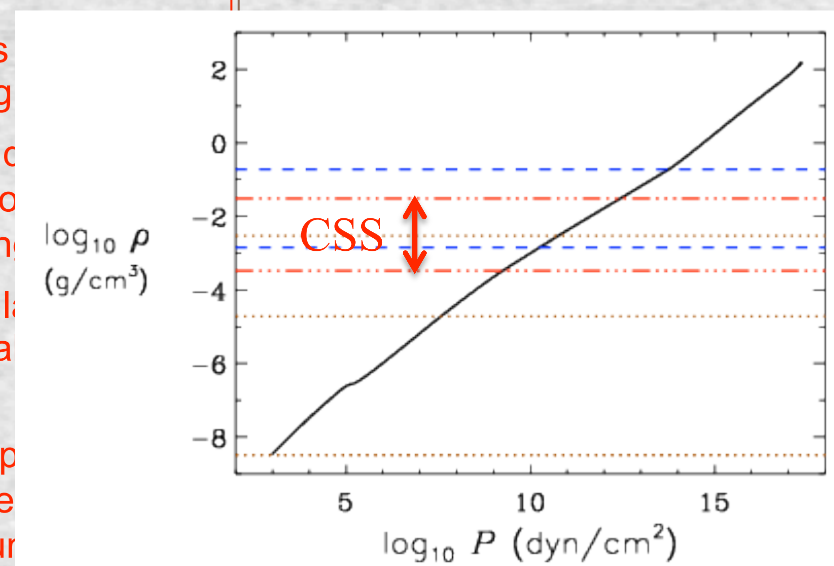
- Lower boundary condition includes latitudinal entropy gradient (Rempel 2005)
- Upper boundary (region) includes enhanced unresolved radial flux

CSS
(Compressible Spherical Segment):

- Compressible dynamics of an ideal gas in a rotating shell segment
- 6th order compact finite difference spatial discretization, 4th order Runge-Kutta time-stepping scheme
- Longitudinally periodic, latitudinally stress free and impenetrable, radially open or closed
- Stochastic driving of upper boundary possible – either cooling sites (thermal starting plumes) or cool jets (mimicking statistics of down-flows in high resolution granulation simulations)

MSC
(Modular Staggered Convection):



lower surface constant pressure

Bridging the local and global models with CSS:

- Drive the upper boundary with randomly placed granular downflow plumes

Three boundary conditions implemented:

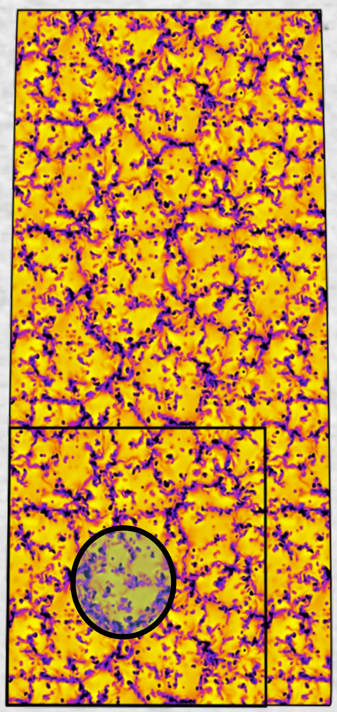
Spherically Symmetric Cooling – a sub-grid scale model of turbulent heat transport that diffusively carries flux through an impenetrable boundary (ASH like)

Starting Plumes – random cooling sites. The cooling strength of each plume scales with the total number of plumes, such that on average they carries the full luminosity, granular lifetimes

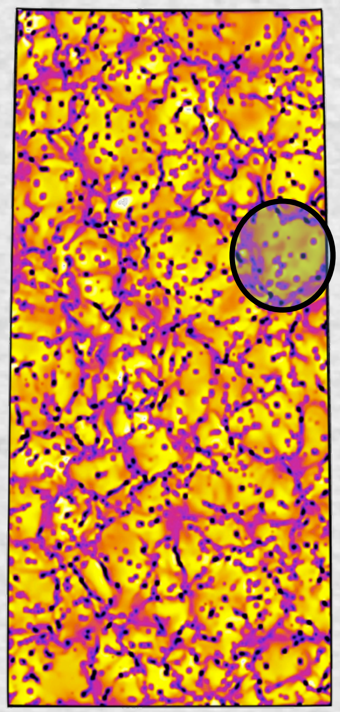
Thermal Jets – random inflows with a velocity, entropy deficit, duration, and size chosen from statistical distributions that mimic the downflow statistics in MSC

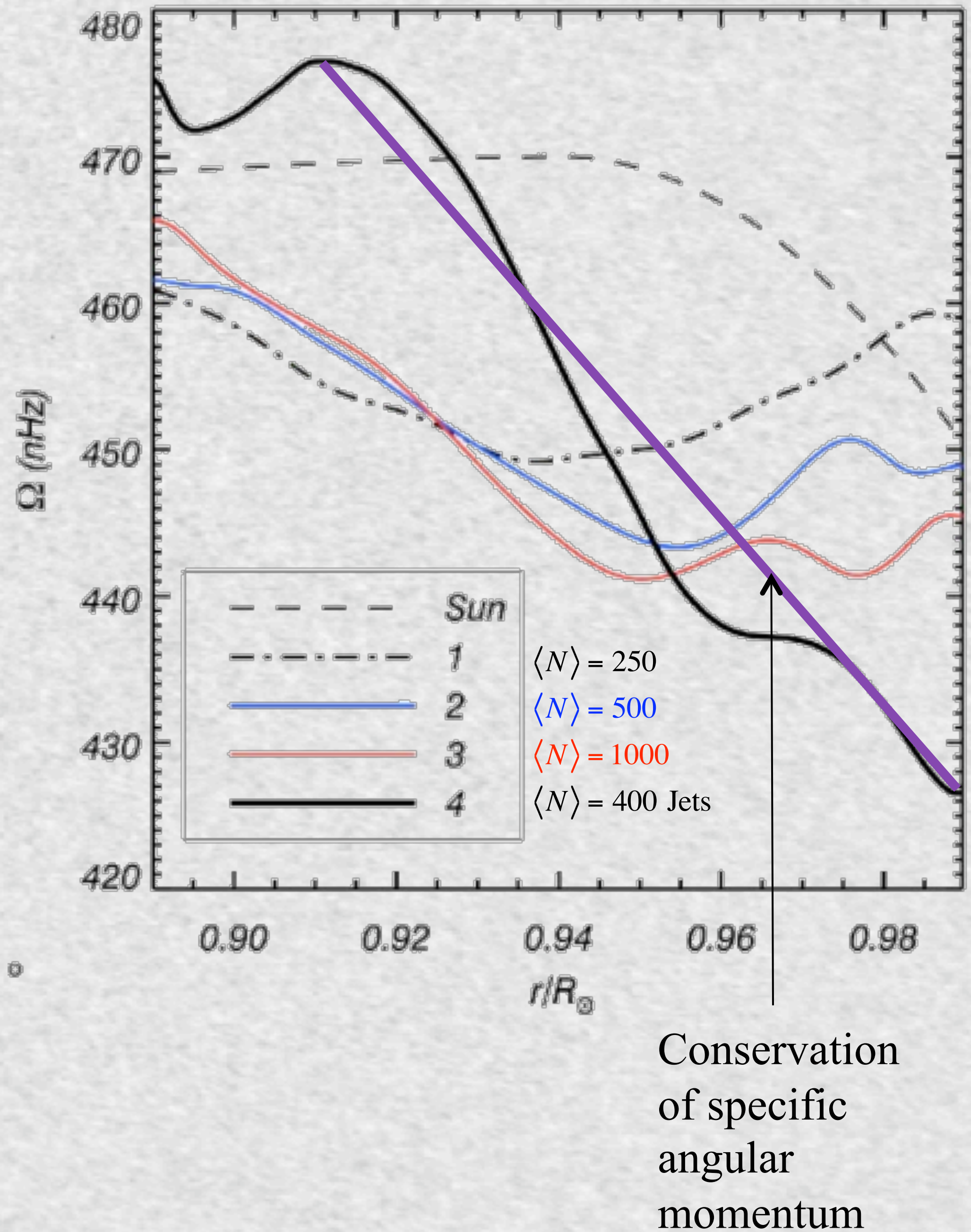
Horizontally averaged rotation rate:

Stein et al. (2009)



CSS:





Questions (which may display more my ignorance of v,v, and uq than anything else):

1. How does one best conduct validation when the validation data is given by observations rather than focused experiments?

   How does one assess which portions of the model are most constrained by the observations at hand, or how well constrained the overall model is by a limited set of observations?

2. What does validation mean in the context of numerical experiments?